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FUNDAMENTALS OF SUBMARINE THEORY

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Department of the Navy  
Washington, D. C.

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### Submarine Draft Marks

Draft marks are used to determine the draft and the immersion of a submarine in the water. They are applied to the submarine's external hull on both sides, three, or two, perpendiculars to the main plane. In the first instance the marks are located at the bow, amidships, and on the stern, while in the latter instance they are located bow and stern, usually at equal distances from the middle frame.

Draft marks (fig. 4) are a series of numbers placed perpendicular to the main plane. The lower edge of each number indicates its elevation over the lower part of the submarine's hull, measured vertically. The perpendicular height of the numbers, with respect to the main plane, and the distance between them, equals 0.10 meter. Accordingly, the active waterlines \* in Figure 4 equal:  $V_1 L_1 = 3.20$  m;  $V_2 L_2 = 3.50$  m; and,  $V_3 L_3 = 3.65$  m.

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\* The waterline to which the submarine is immersed in the water at any given moment is called the active waterline.

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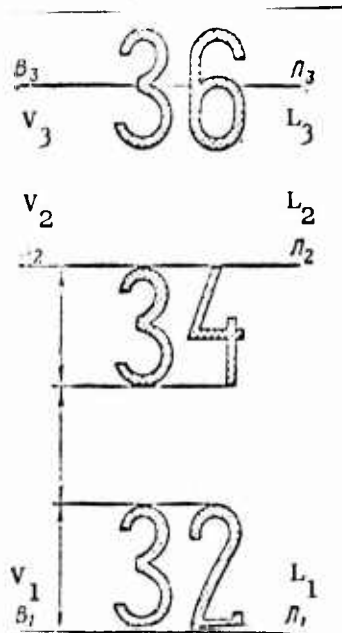


Figure 4. Submarine draft marks.

Draft marks make it possible to determine certain submarine tactical and technical qualities, so various methods are used to disguise the draft indications. For example, draft marks are made in the form of a vertical series of horizontal bands (fig. 5). In this case the draft readings are made from the zero band, or line. The lower edge of the zero band is drawn at a distance  $Z_{o_2}$  from the lower edge of the most deeply submerged part of the submarine's hull.

The vertical distances between the lower edges of adjacent bands for the draft marks are made 0.10-0.20 meter. The zero band is made longer, or is marked with the number 0. Conventional numbers, 2, 4, etc., are placed opposite some of the bands to make reading convenient.

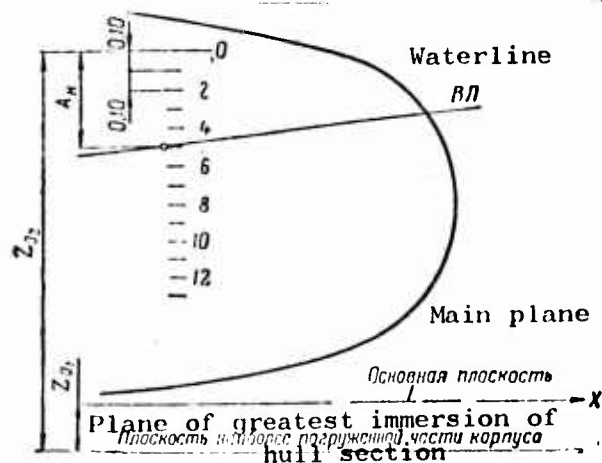


Figure 5. Concealed submarine draft marks.

In order to calculate the submarine's draft, the distance of the active waterline from the lower edge of the zero band at the bow,  $A_b$ , and stern,  $A_s$ , must be determined and substituted in formula (5).

$$\left. \begin{aligned} T_{o_b} &= Z_{o_2} - A_b, \text{ meters} \\ T_{o_s} &= Z_{o_2} - A_s, \text{ meters} \end{aligned} \right\} \quad (5)$$

Draft is distinguished from submergence by the magnitude  $Z_{o_1}$ .

The theoretical plan usually shows the submergence, rather than the draft. Draft immersion can be computed using the formulae in (6).

$$\left. \begin{aligned} T_b &= T_{o_b} - Z_{o_1} = Z_{o_2} - (A_b + Z_{o_1}), \text{ meters} \\ T_s &= T_{o_s} - Z_{o_1} = Z_{o_2} - (A_s + Z_{o_1}), \text{ meters} \end{aligned} \right\} \quad (6)$$

### #3. Submarine attitude and its determination.

A submarine's attitude is its position relative to the calm surface of the water. The position of the submarine relative to the calm surface of the water is entirely determined by the active waterline (DVL) or the totality of such parameters as

$$T_{o_{av}}, T_{o_b}, T_{o_s} (T_{av}, T_b, T_s), \psi(\Delta), \text{ and } \Theta,$$

where

$\psi$  is the submarine's trim angle;

$\Delta$  is the linear trim, meters;

$\Theta$  is the list.

Let us consider the possible cases of submarine attitudes.

1. The submarine (fig. 6) is upright, that is, has no list ( $\theta = 0$ ), and is on an even keel, that is, it has no trim ( $\psi = 0$ ).

In this case the active waterline is parallel to the main, or base, plane. The submarine's attitude is entirely determined by its mean draft (immersion), and this, in turn, is found from the dependencies:

$$\begin{aligned} T_{o_{av}} &= T_{o_b} = T_{o_s}, \text{ meters} \\ T_{av} &= T_b = T_s, \text{ meters} \end{aligned} \quad (7)$$

2. The submarine is upright ( $\theta = 0$ ), but is trimmed by the bow or by the stern ( $\psi \neq 0$ ) (fig. 7) \*. In this case the middle-line plane remains vertical, but the active waterline,  $V \psi L \psi$  is at some angle  $\psi$  to the base plane. The attitude will be characterized by the draft (immersion) at bow and stern, or by the mean draft (immersion) and trim of the submarine:

$$\begin{aligned} T_{o_b}, T_{o_s} (T_b, T_s), \text{ meters} \\ T_{o_{av}} (T_{av}), \psi (\Delta), \text{ meters} \end{aligned} \quad (8)$$

\* In Figure 7, and henceforth, for convenience in depicting the situation, we will rotate the waterline by the corresponding trim angle and list, and not show the submarine with list and trim.

Trim can be measured by the angle in degrees, or in radians, as well as in linear values, such as meters, for example. The most convenient way for submarines to measure trim is in angular degrees, using bubble and mechanical trim angle indicators, or communicating vessel type trim angle indicators (fig. 8).

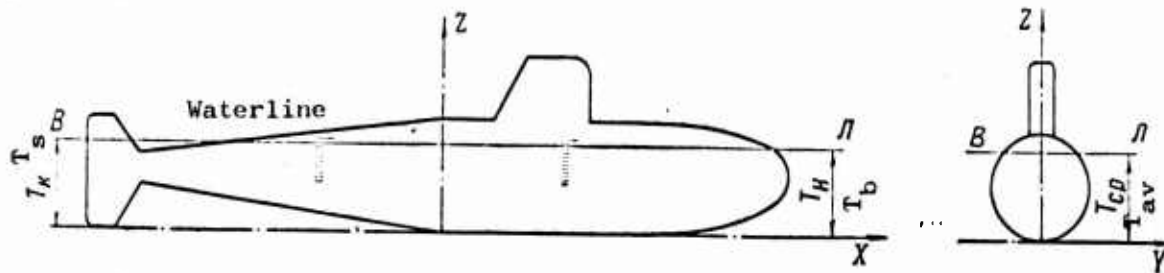


Figure 6. Submarine attitude: upright and on even keel.

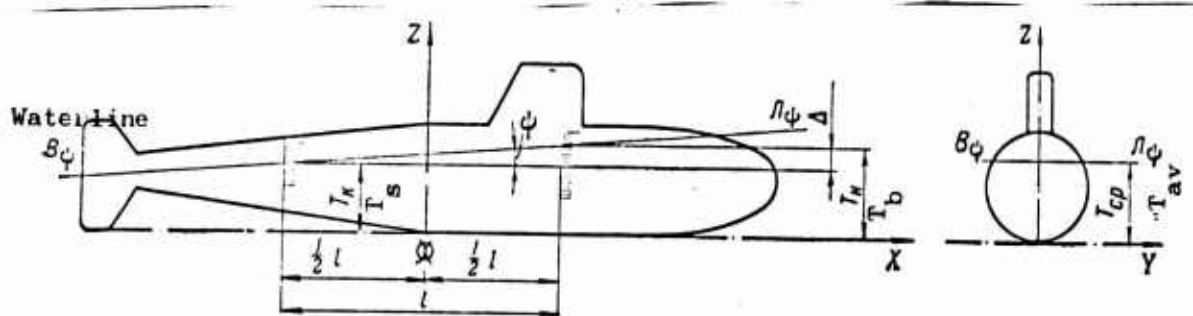


Figure 7. Submarine attitude: upright, but with trim on.

Trim angle can also be calculated with an accuracy of within  $0.1^\circ$  by use of formula (9), which is:

$$\begin{aligned} \tan \psi &= T_{o_b} - T_{o_s} / l = T_b - T_s / l ; \\ \psi^\circ &= 57.3 \times T_{o_b} - T_{o_s} / l = 57.3 \times T_b - T_s / l , \end{aligned} \quad (9)$$

where

$l$  is the distance along the length of the submarine between the bow and stern draft marks, in meters.

The difference in draft readings (immersion) at bow and stern is the linear trim,  $\Delta$ , in meters.

$$\Delta = T_{o_b} - T_{o_s} = T_b - T_s , \text{ meters.} \quad (10)$$

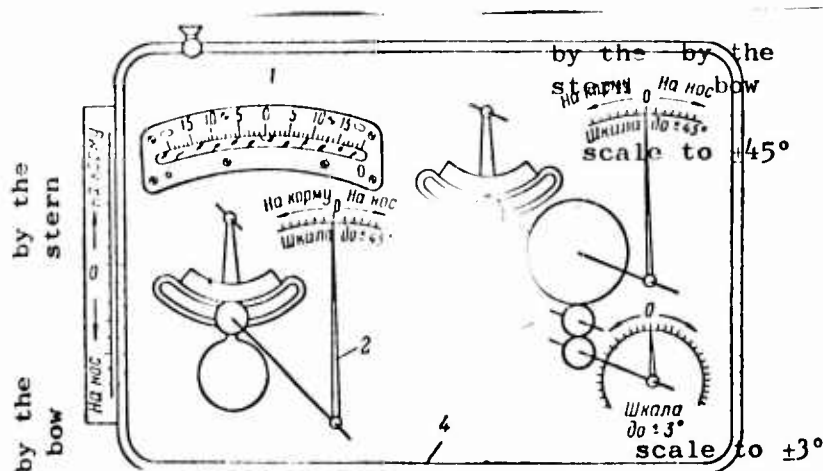


Figure 8. Submarine trim angle indicators. 1 - bubble trim angle indicator; 2 and 3 - kinematic schematics of mechanical, single and double-pointer trim angle indicators; 4 - communicating vessels type trim angle indicator.

When  $T_{o_b} > T_{o_s}$  ( $T_b > T_s$ ) the submarine is trimmed by the bow. Trim angle,  $\psi$ ; and linear trim,  $\Delta$ , have positive values. When  $T_{o_b} < T_{o_s}$  ( $T_b < T_s$ ), the submarine

is trimmed by the stern. Trim angle,  $\psi$ , and the linear trim,  $\Delta$ , have negative values.

That attitude of the submarine in which it is upright, but with trim on is characteristic for the cruising situation in which submarines have, as a rule, a trim by the stern of from 0.25 to 0.50°.

3. The submarine is on an even keel ( $\psi = 0$ ), but has a list ( $\theta \neq 0$ ) to starboard, or port (fig. 9). In this case the middle-frame plane remains in the vertical, but the active waterline,  $V_0 L_0$ , is at an angle  $\theta$  to the base plane. The attitude of the submarine can be characterized by the mean draft (immersion) and the list:

$$T_{o_{av}} (T_{av}), \theta. \quad (11)$$

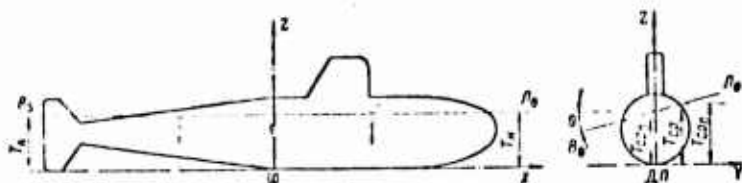


Figure 9. Submarine attitude: even keel, but with list.

The drafts (immersions) at bow and stern when listed differ for starboard and port sides, while the mean draft (immersion) is equal to:

$$\begin{aligned} T_{o_{av}} &= T_{o_{bs}} + T_{o_{bp}} + T_{o_{ss}} + T_{o_{sp}} / 4, \text{ meters;} \\ T_{av} &= T_{bs} + T_{bp} + T_{ss} + T_{sp} / 4, \text{ meters.} \end{aligned} \quad (12)$$

List on the submarine is determined from a pendulum inclinometer (fig. 10), or can be calculated using a special formula (cf., #21). List to starboard is considered positive; to port, negative.

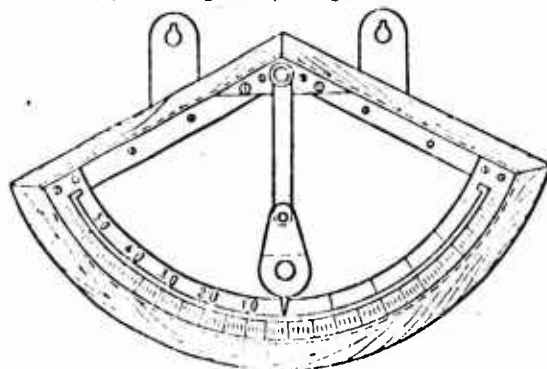


Figure 10. Submarine pendulum inclinometer.

4. The submarine is resting in the water in an attitude such that it has list and trim on simultaneously (fig. 11). Its attitude in this case is determined by the drafts (immersions) at bow and stern, and by the list; that is by the values for

$$T_{o_b}, T_{o_s} (T_b, T_s), \theta, \quad (13)$$

where

$$T_{o_b} = T_{o_{b_s}} + T_{o_{b_p}} / 2 \text{ meters and } T_{o_s} = T_{o_{s_s}} + T_{o_{s_p}}, \text{ meters,}$$

or the mean draft (immersion) is determined from the dependency in (12) and the lists and trims:

$$T_{o_{av}} (T_{av}), \psi (\Delta), \theta. \quad (14)$$

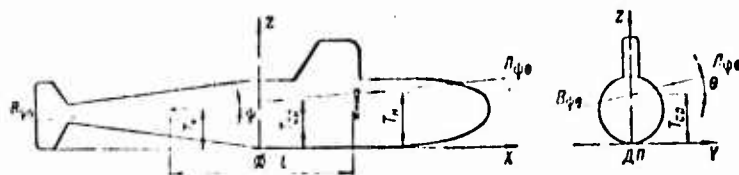


Figure 11. Attitude of a submarine with list and trim on.

The most characteristic attitude for a submarine is one in which it is upright, but with a slight trim by the stern. Other attitudes can be encountered when actually cruising, in emergencies, or during various operations.



#13. Main surface and submerged conditions for submarines.

Submarines can be found in one of the following main conditions, depending on the loading and filling of the main ballast tanks: diving trim at full buoyancy; trimmed down; or submerged.

When in diving trim at full buoyancy the submarine is surfaced and trimmed, the quick-diving tanks are full \* and the main ballast tanks are blown. The submarine is in diving trim at full buoyancy, ready to submerge at any moment. The diving trim at full buoyancy condition corresponds to a cruising displacement of  $V_c$  in cubic meters.

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\* The quick-diving, or negative, tanks (TsBP) are special tanks designed to give the submarine residual negative buoyancy during submergence, as well as trim by the bow to reduce submergence time. The weight of the water in such tanks does not enter into cruising displacement.

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Diesel propelled-storage battery submarines have different diving trims at full buoyancy when carrying normal fuel and when carrying greater than normal fuel supplies.

With a normal fuel supply the displacement is  $V_c = V_s + V_f$ , where  $V_f$  is the volume of the normal supply of fuel and lubes for assigned cruising ranges at full and economical speeds, in cubic meters, and  $V_s$  is the standard displacement, in cubic meters. The standard displacement is the <sup>s</sup>displacement of a completely built submarine, together with crew and fitted out with all the necessary equipment and supplies, with the exception of fuel and lubes.

Displacement  $V = V_c + V_{fbt}$  is the displacement in diving trim at full buoyancy with greater than normal fuel supplies on board.  $V_{fbt}$  is the volume of the fuel and ballast tanks, in cubic meters. \*\*

In the trimmed down condition on the surface the submarine is trimmed and the negative tanks are blown, but the main ballast tanks are full, with the exception of the amidships group of tanks, which are blown. Displacement in the trimmed down condition is

where  $V_{td} = V_c + V'_{mb}$ , in cubic meters,

$V'_{mb}$  is the volume of the bow and stern (or fore and aft) groups of main ballast tanks, in cubic meters.

The trimmed down condition is intermediate in the emersion when in diving trim at full buoyancy.

The submerged condition is the condition of a trimmed down submarine submerged with full main ballast tanks, but with the negative tanks blown. The

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\*\* The fuel-ballast tanks are the main ballast tanks which can be adapted for the storage of liquid fuel.

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submerged condition corresponds to a displacement

$$V_m = V_c + V_{mb} = V_c + V_{fs}, \text{ cubic meters,}$$

where

$V_{mb}$  is the volume of the main ballast tanks, in cubic meters;

$V_{fs}$  is the full submergence volume, in cubic meters.

When making calculation, attention must also be given to the full submerged displacement

$$V_{mf} = V_c + V_{mb} + V_{hp}, \text{ cubic meters,}$$

where

$V_{hp}$  is the volume of all submarine hull parts into which the water can penetrate, in cubic meters.

Submarines can be said to be submerged to periscope depth, to snorkel (RDP)\* depth, and to depths ranging from safe to limiting, depending on the depth of the submergence.

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\* The RDP is the installation which permits use of diesel engines at periscope depth.

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Periscope depth of submergence ( $H_{per}$ ) is that depth at which it is possible to make periscope observations of the horizon and of the air from a submerged submarine. The depth will depend upon the type of submarine, and the sea state, and will range from 8 to 11 meters.

Snorkel depth ( $H_{RDP}$ ) is that depth at which the RDP installation will function and at which periscope observations can be made. The depth depends upon the type of submarine. It is equal to, or less than, the periscope depth.

Safe submergence depth ( $H_{sd}$ ) is that depth at which the possibility of collision with surface ships is eliminated. It is equal to 25 to 30 meters.

Operating depth ( $H_{od}$ ) is the deepest submergence at which the submarine can remain underway for long periods of time. The operating depth is 70 to 90% of the limiting depth.

Limiting depth ( $H_{ld}$ ) is that greatest depth at which the submarine can arrive at without way on; on the bottom, for example, or underway periodically. A submarine cannot, as a rule, be underway at its limiting depth. The reason is that submarine movement takes place with a variable trim, along some curve which is oriented with respect to the particular depth. Consequently, if the submarine is underway at its limiting depth it will submerge beyond that depth periodically, and this is not permissible in normal operations. This factor has also resulted in the necessity for assigning operating depths. The limiting depth for modern submarines is from 400 to 500 meters.

The designed diving depth ( $H_{dd}$ ) determines the reserve strength in the

in the submarine's pressure hull and exceeds the limiting depth by from 30 to 50%. This is the depth at which destruction of the submarine's pressure hull can begin. The submarine should not appear at this depth except in case of emergency.

#29. Concepts of the Experimental Determination of the  
Transverse Stability of Submarines.

The experimental determination of the transverse metacentric height (inclining) is made on the lead submarine of each series in the diving trim at full buoyancy and submerged conditions. \* It is usually combined with test submergence and weighing. Generally speaking, transverse stability is determined by experiment only in the submerged condition for serial submarines. Surfaced stability is calculated for the lead submarine, and a correction factor is added to cover its deviation from the submarine which was tested. The correction factor is determined to be the difference in submerged stability between the test and the lead submarines.

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\* It is not usual to make an experimental determination of longitudinal stability.

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It is recommended that the inclining experiment be done in a protected body of water, where there are no currents, and where the depth is great enough for the submarine to submerge to periscope depth without touching the bottom. It is permissible to put out lines at bow and stern in the longitudinal plane to hold the submarines. The lines should be slack enough not to interfere with the experiment. Submarine loading should be either special, or normal. Small shortages and surpluses in cargo (ballast for the inclining experiment, equipment for the experiment, etc.) are allowed for in a special list of excessive and deficient loads. It is mandatory that the submarine be weighed prior to the inclining experiment.

Ballast for the inclining experiment is taken on in the form of cast-iron pigs with a total weight equal to at least  $0.005 \gamma V_c$ . When determining above water stability the ballast is placed on special bridges on the upper deck, whereas, during the inclining experiment submerged it is placed on deck in the clearest and widest compartments. The balances used to measure the list, at least two of them, are usually suspended in the access trunks to the central station and in the access trunk to one of the end compartments. The list is read on a wooden batten (fig. 57). It enables the finding of  $\tan \theta = BC/AB$ .

The lower end of the balance is placed in a container of oil or water in order to reduce its oscillation. The zero position of the balance is recorded before the ballast is put in place, after which the ballast is shifted, in equal parts, from side to side, and back again, and the deflection of the balance is recorded each time.

The substance of the experiment is as follows. When ballast is shifted from side to side, say in the surfaced condition, for example, (fig. 58), the submarine's center of gravity will shift from  $G$  to  $G_1$ . The displacement  $GG_1$  is determined from the theorem concerning the displacement of the center of gravity of the system of forces:

$$\overline{GG_1} = pl_p/P = pl_p/\gamma V ,$$

where:

$p$  is the weight of the ballast shifted at one time, tons;

$l_p$  is the arm of the ballast displaced, meters;

$P = \gamma V$  is the weight of the submarine at the time of the experiment, tons.

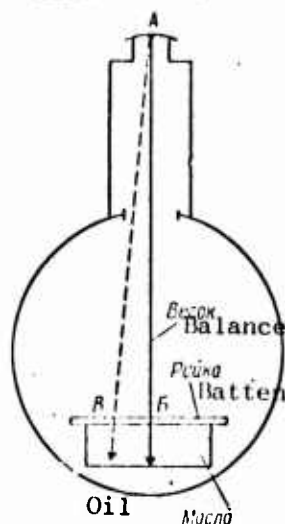


Figure 57. Determination of list during the inclining experiment.

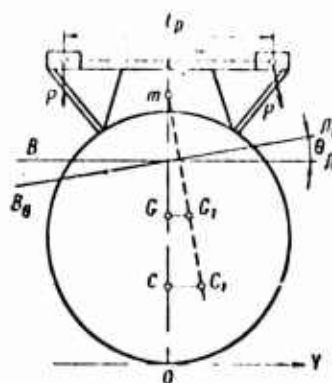


Figure 58. Determination of the transverse stability by experimental means.

From triangle  $GmG_1$  we find

$$\overline{GG_1} = \overline{Gm} \tan \Theta .$$

Equating the right members, we obtain

$$pl_p/P = \overline{Gm} \tan \Theta ,$$

from whence

$$\overline{Gm} = pl_p/P \tan \Theta , \text{ in meters.} \quad (181)$$

All the values are known in this dependency for determining the transverse metacentric height,  $\overline{Gm}$ . The transferable ballast,  $p$ , is weighed in advance. The displacement arms,  $l_p$ , are determined and measured in advance. The submarine's weight,  $P$ , during the experiment is determined from the loading and the draft marks. The magnitude of the list,  $\tan \Theta$ , is determined from the inclination of the balance.

Determining the transverse metacentric height,  $\overline{Gm}$ , from the experiment, and calculating  $r$ ,  $A_m$  and  $Z_c$  for the load  $P$  from the theoretical drawing, it is also easy to find  $Z_g$ :

$$\begin{aligned} Z_g &= Z_m - \overline{Gm} , \text{ meters } ) \\ Z_g &= Z_c + r - \overline{Gm} , \text{ meters } ) . \end{aligned} \quad (182)$$

To obtain the operable values for transverse metacentric height and for the Z-axis of the center of gravity of the submarine in the condition of diving trim at full buoyancy and in the submerged condition in the values for  $\overline{Gm}$  and  $Z_g$  obtained during the experiment we introduce correction factors in accordance with the summary from the list of shortages and overages in cargo, using for these purposes the dependencies for determining the stability of the submarine upon receipt (consumption) of the cargoes (#22 and #26).

#40. Calculation for righting damaged submarines using  
the method of counter flooding the main ballast tanks.

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Righting (counterflooding) a damaged submarine can result in some improvement in its surface maneuvering qualities, and thus restore its ability to submerge, surface, and operate submerged. The minimum required to do this is to plug the hole and to pump out the damaged compartment.

Righting a damaged submarine envisages reducing its list and trim to values close to zero. There are three methods, or combinations of them, which can be used principally for this purpose:

shifting cargo inside the submarine;

removing the cargo;

counterflooding undamaged main ballast tanks (by taking on cargo).

The advantage in the first method is that it does not require using up any reserve buoyancy. When the second method is used reserve buoyancy is even somewhat increased. The disadvantages of both of these methods are: righting takes a lot of time; use is extremely limited because there is not enough cargo to shift and throw overboard; preliminary calculations are impossible to make; the submarine's trim is upset and additional time is required to restore it when the possibility of submerging arises.

The third method calls for the use of reserve buoyancy for accomplishment. This is its basic shortcoming. The use of the method is limited; there are few main ballast tanks. The positive aspects of the method include: retention of submarine's trim; the possibility of computing righting for all characteristic cases of casualties in advance; little time is required to right; ease of restoration of submarine's diving trim at full buoyancy by blowing full main ballast tanks.

The counterflooding method for surface ships was introduced by Admiral S. O. Makarov as far back as 1870. He made it mandatory on surface ships of the Russian fleet between 1903 and 1905. Thanks to the work of I. G. Bubnov, A. N. Krylov, and V. G. Vlasov, the counter flooding method was introduced in an orderly system of ensuring the unsinkability of surface ships and submarines, based on strict mathematical calculations.

In essence, the method involves filling undamaged main ballast tanks in order to right a damaged submarine. The tanks thus filled are opposite those causing the list and trim, and this must be due to flooded or damaged compartments and main ballast tanks. There is a simultaneous reduction in list and trim of the damaged submarine and there is less use of the reserve buoyancy. At the basis of the method is the famous instruction given by A. N. Krylov that reserve buoyancy should be used up completely and in advance of the submarine losing stability.

When counter flooding of main ballast tanks occurs there is an improvement in transverse stability, controllability, performance, and rolling conditions, the result of the use of the reserve buoyancy. In other words, there is an improvement in the entire complex of sea-keeping qualities for a surfaced submarine.

The following must be known in order to use the main ballast tank counter flooding method correctly, and in timely fashion, and this applies to every case in which a casualty is involved: first, whether or not righting is necessary; second, whether it is possible, or not, to right the boat; and, third, should such counter flooding be necessary and possible, which of the main ballast tanks to flood.

The amount of list and trim determine the need for righting. Righting is usually necessary when the list exceeds 2.5 to 3.0°, and the trim 0.5 to 1.0° (greater trim values are trim by the stern). Accordingly, a list and trim of the values indicated are sufficient for righting.

The possibility of righting a damaged submarine is determined by its reserve buoyancy and transverse stability. Reserve buoyancy remaining after righting should be sufficient to ensure safety of navigation. Its magnitude is selected from the engineering documents for the submarine. The transverse stability of a damaged submarine after it has been righted should be at least equal to that of its stability in the trimmed down position.

The calculation for righting a damaged submarine by the main ballast tank counter flooding method is carried out in the following manner:

1. compute stability and draft for the damaged submarine (#39) for a number of possible cases of flooded compartments and main ballast tanks;
2. select for counter flooding those main ballast tanks such that their summed  $m_{l_{mb}}$  and  $M_{t_{mb}}$  will approach the list and trim moments of the compartments and main ballast tanks flooded as a result of the damage, and will be of opposite signs. The volume of the main ballast tanks flooded should be minimum for satisfying righting conditions;
3. compute the stability and draft of the damaged submarine after righting (#39). In this case the initial position taken is that for the stability and draft of the damaged submarine prior to righting.

If the results of the calculations do not satisfy the conditions which will determine righting the boat, make a new selection of main ballast tanks and do the calculations again. These calculations are repeated until such time as the needed results are obtained.



**//45. Tables for independent surfacing from the bottom of damaged submarines.**

The tables are systemized data from calculations for independent surfacing of a damaged submarine with flooded compartments and damaged main ballast tanks.

Tables for independent surfacing from the bottom (Table 18) can be compiled according to tables of the type used for surface unsinkability. They should show:

types of casualties connected with the flooding of compartments in the pressure hull and with damage to main ballast tanks in the pressure hull on the same side of the submarine;

the condition of the damaged submarine on the bottom;

measures which will provide for independent surfacing (trimming, main ballast tanks which can be blown);

condition of the damaged submarine upon surfacing;

the submergence depths from which a damaged submarine can surface independently with its available reserve of high pressure air

The curves which are part of the table (fig. 87) make it possible to determine immediately, and without calculations of any sort, the surfacing depth and the quantity of high pressure air needed for surfacing the boat in each concrete case of damage.

When the decision is made to surface independently, the corresponding damage case is found in column 2 of Table 18, and then the variants for trimming, and the number of the main ballast tanks to be blown, are found in the corresponding lines. The damaged submarine is then trimmed in accordance with the variant selected, followed by the blowing of the main ballast tanks indicated in the surfacing variant selected.

Table 18.

Damage Авария					Surfacing Погружение				Примечание
№ случая аварии	Затопленные отсеки и поврежденные цистерны главного балласта	Остаточная отрицательная плавучесть, т	Дифференцирующий момент, тм	Продольная и поперечная метacentрические высоты, м	Цистерны главного балласта, подлежащие продуванию	Дифферентовка перед всплытием	Ожидаемый дифферент при всплытии, град	Продольная и поперечная остойчивости при всплытии, м	
1	2	3	4	5	6	7	8	9	10
1									

1 - No. of damage situation; 2 - Flooded compartments and damaged main ballast tanks; 3 - Residual negative buoyancy, tons; 4 - Trimming moment, tons/meter; 5 - Longitudinal and transverse metacentric heights, meters; 6 - Main ballast tanks which can be blown; 7 - Trim before surfacing; 8 - Expected trim during

surfacing, degrees; 9 - longitudinal and transfer stability during surfacing, meters; 10 - Notes.

The same conventional symbols used in Table 14 were used here.

NOTES: 1. As will be seen from the manner in which the table is constructed, one type of damage should, as a minimum, have two surfacing variants, and each of these, in turn, should have two or more trimming variants.

2. Column 7 must contain exact information on how to trim, that is, where, and how much ballast to take on; from where, and how much, as well as what kind, of cargo to remove from the boat; the tanks between which liquid cargo is to be shifted, what kind, and how much (for example, Auxiliary Tank No. 1 - overboard 1.0 ton, etc.).

3. The calculation for stability is made in accordance with generally accepted rules for taking on cargo.

In conclusion, it should be noted that modern submarines, such as those with atomic power, for example, are capable of running at high submerged speeds for long periods of time and can be held with comparatively high values for residual negative buoyancy by creating trim by the stern and by shifting the horizontal rudders accordingly (#73). This property of high-speed submarines is an important factor in ensuring submerged unsinkability and definitely causes this latter to approach optimum requirements (#42).

### #55. The Speed Trials Concept.

Submarine speed trials are designed to determine maximum underway speed (on the surface, when operating on snorkel, and submerged), as well as to determine the dependence between underway speed, propeller shaft rpm (main engines) and main engine power outputs. Speed trials are also used to determine fuel consumption (or other power source utilization), lube oil consumption, etc., per mile covered at various speeds, as well as to determine economical speed and cruising radius (#53). If the submarine has the necessary gear installed propeller thrust is also measured.

Speed trials are conducted with all lead submarines in a series, as well as with all submarines built outside the various series, prior to commissioning, and with submarines which have completed modernization and major overhauls.

Speed trials are conducted on a course measuring from 3 to 5 miles in length. The measured "mile" is a section of the sea with adequate depth and specially fitted out with ranges for departure and taking cuts required as the test progresses. The area in which the measured "mile" is located should have sufficient maneuvering room for the submarine.

The submarine is docked prior to speed trials and the hull is cleaned and painted, while propellers are checked for proper operating condition.

Trials are made on the surface in the trimmed down condition with full ballast, under snorkel, and submerged to periscope depth. List is not permitted during the trials.

The following basic measurements are made during the trials.

First, underway speed relative to the water, in accordance with the markers along the course, is determined. A stop watch is used to record the time of the run over the course. At least three runs are made; to eliminate the effects of current. Two runs are made in one direction, one in the opposite direction. True speed is determined from the dependency

$$v_{\text{submarine}} = l_{\text{mm}} / \frac{1}{2}(1/t_1 + t_3 + 2/t_2), \text{ miles/hour}, \quad (307)$$

where

$l_{\text{mm}}$  is the length of the measured "mile" in miles;

$t_1$ ,  $t_2$  and  $t_3$  are the times for the first, second, and third runs over the measured "mile" in hours.

Second, the shaft rpm are recorded. Revolutions made on each run can be determined from the revolution counter, or with contact rings. The true rpm,  $n$ , can be determined from the dependency

$$n = 0.25(n_1 + 2n_2 + n_3), \text{ rpm}, \quad (308)$$

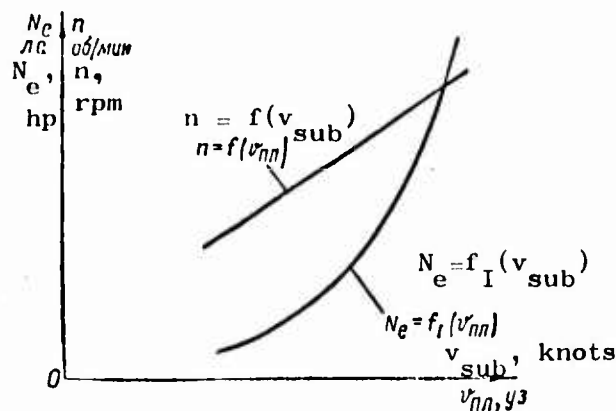


Figure 106. Dependence of power and rpm on submarine's underway speed.

where

$n_1$ ,  $n_2$ , and  $n_3$  are the rpm on the first, second, and third runs, rpm.

Third, the main engine power outputs are measured. Power output is determined using torsigraphing, indicating, or other means which can be used, on each run. True power,  $N$ , is found from the dependence similar to that shown as formula (308).

Fourth, fuel consumption (or other power source consumption) is determined per mile covered at the given speed. True fuel consumption,  $q_M$ , per mile can be obtained from a dependency similar to that shown in formula (308).

Fifth, propeller thrust is measured, if the necessary gear is available in the submarine.

The results of the speed trials are processed to compile tables and to construct curves for surface, snorkel, and submerged runs: (1) for power and rpm according to underway speed on the surface and submerged (for surface running, figure 106, for example); (2) for fuel (or other power source) consumption per mile according to speed and main engine combination used; (3) cruising radius according to speed and main engine combination used, etc.

It is recommended that speed trials be run without interruptions, and that they be run off when the weather is good (wind force no higher than two and sea state no higher than one), in order to eliminate the effects of outside conditions.

## Chapter XI

### Submarine Control in the Horizontal Plane

#### #61. General Concepts and Determination.

By control in the horizontal plane is understood to mean the ability of a submarine to maintain a given course and to be able to change that course by the use of the vertical rudder and the propellers. Control in the horizontal plane is an extremely important sea-keeping quality for a submarine. It makes it possible to carry out all maneuvers in the horizontal plane needed to carry out the combat missions assigned submarines.

The general behavior patterns in the control of a submarine in the horizontal plane are the same as those for the surface ship. However, and as distinguished from the surface ship, the submarine must have control in the horizontal plane not only on the surface, but when submerged, when surfacing, and when submerging. Since the processes of submerging and surfacing are of brief duration, and since the behavior patterns involved in control in the horizontal plane are similar for all positions in which the submarine can be found, we will consider submarine control in the surfaced and submerged conditions only.

Submarine control in the horizontal plane is the sum of the steadiness on course (steadiness of movement in the horizontal plane) and turning ability.

Steadiness on course is that ability of submarines to move on a straight line along an assigned course when the rudder is amidships.

Turning ability is that ability of submarines to change course as a result of the effects of the vertical rudder and the propellers.

As we can see, the requirement for steadiness on course and for turning ability are mutually contradictory. Therefore, what is required is that combination of the qualities noted which will, to the greatest extent possible, provide the tactical requirement for submarine maneuvering qualities for the particular class and type, and thus provide the submarine with good control in the horizontal plane.

Immediate note should be made of the fact that the submarine, by itself, is not steady on course any more than is the surface ship. The vertical rudder must be shifted constantly to hold the submarine on course. The usual consideration is that steadiness on course is adequate when the helmsman shifts the rudder  $\pm 2$  to  $3^\circ$  (to starboard or port) not more than 8 to 10 times per minute.

Thus, the primary organ providing control in the horizontal plane is the vertical rudder. However, in multi-shaft main propulsion installations the propellers can, to some degree, provide control in the horizontal plane. Limited control in the horizontal plane can be exercised with other, special, methods, such as creating a list and by the actions of the horizontal rudders.

#78. The V. G. Vlasov Roll Diagrams and Their Use.

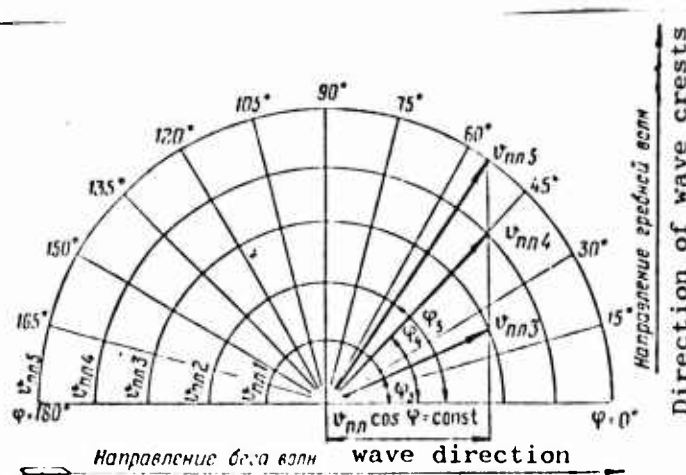


Figure 148. V. G. Vlasov roll diagram grid.

The V. G. Vlasov roll diagrams are circular diagrams, or charts (fig. 148), on which speed and course angle for the submarine are shown by radii. The length of the radius, drawn to scale, shows the magnitude of the underway speed, while its direction shows the course angle relative to the direction in which the waves are running. The wave crests have a vertical direction on the roll diagrams. The direction in which the waves are running is selected such that the submarine is perpendicular to the crests when  $\phi = 0$ , and when  $\phi = 90^\circ$  it is parallel to the crests. When  $\phi = 180^\circ$  the submarine is perpendicular to the crests, but opposite to wave direction.

We have, in order to clarify the principle involved in the construction of the roll diagrams, converted dependency (412) by substituting in it as a replacement for the wave speed,  $S_w$ , the value found for it in dependency (398):

$$\tau_{apw} = \lambda_w / S_w - v_{sub} \cos \phi = \lambda_w / 1.25 \sqrt{\lambda_w} - v_{sub} \cos \phi. \quad (414).$$

As will be seen from (414), some particular wave, designated by length  $\lambda_w$ , has an apparent period,  $\tau_{apw}$ , which has the same identical value for many combinations of course angle,  $\phi$ , and submarine underway speed,  $v_{sub}$ , since the derivative  $v_{sub} \cos \phi = \text{constant}$ , can be obtained for many values of  $v_{sub}$  and  $\phi$ . The derivative  $v_{sub} \cos \phi$  is depicted on roll diagrams by a vertical straight line. Accordingly, any vertical straight line on roll diagrams corresponds with the same identical apparent period for the waves for different values for  $v_{sub}$  and  $\phi$  (fig. 148).

However roll diagrams do not include scales for the wave periods or for submarine roll periods. In order to draw some value for the apparent period for the waves,  $\tau_{apw}$ , on the diagram we must find the corresponding apparent period for submarine underway speed when  $\phi' = 0$ , using equation (414). Then, assigning values to  $\tau_{apw}$ , we find the underway speed,  $v_{sub}$ , corresponding and plot them on the horizontal base of the diagram. Erecting perpendiculars at the points thus obtained, we get all the possible variants for the relationship of  $v_{sub}$  and  $\phi'$  for the given value of  $\tau_{apw}$  on them.

Solving equation (414) with respect to  $v_{sub}$ , we find

$$v_{sub} = 1.25 \sqrt{\lambda_w} - \lambda_w / \tau_{apw}, \text{ meters/second,} \quad (415)$$

or, expressing  $v_{sub}$  in knots (1 knot = 0.515 meters/second),

$$v_{sub} = 1.94(1.25 \sqrt{\lambda_w} - \lambda_w / \tau_{apw}), \text{ knots.} \quad (416)$$

We can obtain positive and negative values for submarine speed when making the computations. Positive values for the speed are plotted from the center of the diagram to the right, while the negatives are plotted to the left.

The same identical length of a wave correlates to two zones of greatest roll and pitch, located symmetrically relative to the speed of the submarine  $v_{sub}$ , and equal to the wave speed,  $S_w$ :

$$v_{sub} = S_w = 1.25 \sqrt{\lambda_w}, \text{ meters/second} \quad (417)$$

or

$$v_{sub} = S_w = 2.425 \sqrt{\lambda_w}, \text{ knots.} \quad (418)$$

Since every V. G. Vlasov roll diagram corresponds with a completely defined wave length, hydrological data for a given theatre, or geographic region, can be used to select average values for wave lengths,  $\lambda_w$ , say 4, 5, 6, 7, and 8, on the wave scales, and used to construct roll diagrams for such values of  $\lambda_w$  when the submarine will be operating in the theatre or region.

It is not expedient to modify roll diagrams for change in submarine loading. The submarine compensates for cargo used, or taken on. The slight changes in stability occasioned by the changes in load distributions and moments of inertia of the submarine's mass have no marked effect on the nature of its rolling.

Heaviest roll and pitch are noted at resonance; that is, when  $\tau_{apw} = \pm T_\theta$  and when  $\tau_{apw} = \pm T\phi'$ . Pitching is particularly heavy when wave lengths are  $\lambda_w = (1.10 \text{ to } 1.15)L$ . Conventional zones of heavy rolling lie within the limits  $\tau_{apw} = \pm(0.80 \text{ to } 1.20)T_\theta$  and  $\tau_{apw} = \pm(0.85 \text{ to } 1.15)T\phi'$ . Calculating 12 values of  $\tau_{apw}$  for submarine speed,  $v_{sub}$ , and plotting the zones of heaviest roll and pitch on the diagram with conventional hatching, we obtain a V. G. Vlasov roll diagram (fig. 149) for the given wave length,  $\lambda_w$ , and the sea state in the units used to designate such state.

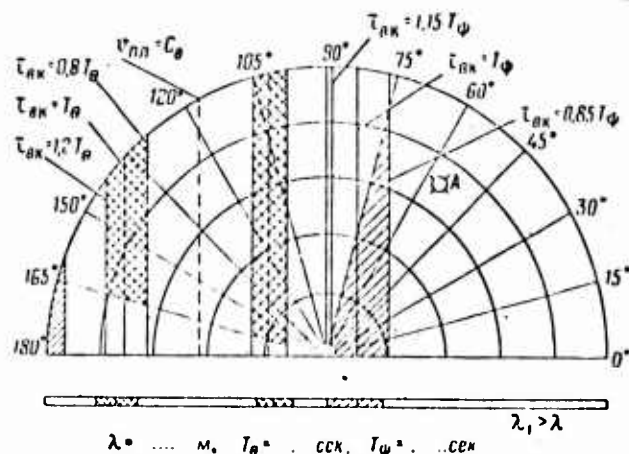


Figure 149. V. G. Vlasov roll diagram.

For practical use, it is recommended that all roll diagrams be constructed on tracing paper to the same scale, and that below each diagram the zones of heavy roll for the nearest long lengths of waves be indicated. Then, by applying one diagram to another, there is no difficulty in determining the nature of the change in the zone of heavy rolling when wave motion increases, and decreases. Naked eye interpolation can be made for the case of wave motion not shown on the diagrams, should the need arise.

The roll diagram in each concrete case is selected for the wave length corresponding to the sea state on the scale. A point corresponding to the submarine's underway speed and course angle, say point A (fig. 149), is plotted on the roll diagram. The position of point A with respect to the heavy rolling zone indicates the situation in which the submarine is found.

Rolling increases markedly upon approaching a zone of heavy rolling and takes on its most intensive form in such zone. Consequently, when steaming and maneuvering the submarine must, in so far as possible, avoid zones of heavy roll and pitch, and particularly the upper sections of the zones of heavy roll and the lower parts of zones of heavy pitching. When a submarine enters the upper section of a heavy roll zone the result is the appearance of great oscillations in roll (list), as a result of which the spilling of electrolyte from the storage batteries, as well as other incidents, are possible. When the submarine enters the lower part of a zone of heavy pitching it will take great amounts of water over the upper deck as it buries its bow and then its stern. There is then the possibility of water entering the hull through open hatches and trunks. Water can cause reduction in insulation and short circuits.

In taking steps to reduce roll it must be remembered that displacement of the submarine along the radius, that is, increasing or decreasing speed without changing course, has little effect on the nature of roll and pitch. The most advantageous speed is that corresponding to the dividing line. Change in the course angle in the ranges of 0 to 45° and 135 to 180° has a marked effect on roll, reducing it when submarine course angles approach 0 and 180°, but there is little effect on pitch. Change in the course angle within limits of from



45 to 135° has a marked effect on pitch, reducing it as the course angle approaches 90°. When the waves are high high submarine speeds should be avoided, particularly when heading into the sea (course angle  $\phi = 180^\circ$ ), for this can result in the waves striking the submarine's hull with great force.

When it is necessary to change speed and course angle, and in order to evaluate the maneuver which will take place, from the point of view of obtaining an acceptable roll, the corresponding roll diagram is selected, the point corresponding with the speed and course angle is plotted for the before and after values, and the change in submarine roll is noted. Then the submarine's course is plotted on the diagram, changing its speed and course angle so as, in so far as is possible, to avoid zones of heavy rolling, or to pass through them at their least dangerous sections, which, for the heavy roll zone is the lower section, and, for the heavy pitch zone is the upper section.